Quest Journals
Journal of Software Engineering and Simulation
Volume 12 ~ Issue 7 (July 2026) pp: 07-17
ISSN(Online) :2321-3795 ISSN (Print):2321-3809
www.questjournals.org

Research Paper

HIRARC And FMEA Analysis for Prioritizing Occupational Safety and Health Risks in High-Rise Building Structural Works

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ABSTRACT: *Structural works in high-rise building projects involve simultaneous interaction among workers, materials, temporary works, and equipment. This study develops a structured occupational safety and health (OSH) risk prioritization at The Arumaya Office Project, South Jakarta, by combining Hazard Identification, Risk Assessment and Risk Control (HIRARC) and Failure Mode and Effects Analysis (FMEA). Nine structural-work hazards were identified from project safety documents, relevant standards, and literature, then validated by three project informants. A pilot survey preceded the main questionnaire distributed to 20 respondents involved in structural work. HIRARC was used to calculate Risk Rating (RR) from likelihood and severity, while FMEA calculated Risk Priority Number (RPN) from severity, occurrence, and detection. The highest HIRARC result was falling from scaffolding or height (V5), with likelihood 4.45, severity 4.85, and RR 21.58. The same risk was also the leading FMEA priority with severity 4.75, occurrence 4.50, detection 3.35, and RPN 71.61. Collapsed formwork (V9) and nail puncture or tripping hazards (V6) ranked second and third. The results demonstrate that HIRARC provides a clear initial risk map, while FMEA strengthens priority setting by considering the detectability of an unsafe condition. Risk response recommendations emphasize work-at-height permits, scaffold inspection and tagging, full-body harnesses, formwork and bracing checks, housekeeping, lifting plans, access zoning, and routine HSE supervision.*

KEYWORDS: *HIRARC, FMEA, occupational safety and health, structural works, high-rise building, risk priority number.*

*Received 02 July., 2026; **R**evised 10 July, 2026; **A**ccepted 12 July, 2026 © The author(s) 2026.*
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I. INTRODUCTION

Construction safety is not an administrative add-on. It is a basic project-management function because workers are continuously exposed to changing work fronts, equipment, materials, and temporary structures. The International Labour Organization notes that construction work combines dynamic work environments with physical hazards that may lead to injury, disability, or fatality when the work system is not planned and controlled effectively [1].

High-rise building construction increases this exposure because activities occur at different elevations and in limited work zones. Structural work includes foundation work, erection, formwork installation, scaffolding, material movement, concrete casting, and temporary works. These activities involve the risk of falls, struck-by events, caught-between incidents, sharp-object injuries, wet-concrete exposure, and failure of temporary structures [4], [5].

The Arumaya Office Project was selected because its structural phase includes a variety of high-risk activities. The project has four basement levels and approximately twenty-three podium and tower floors. The interaction between vertical material movement, work-at-height tasks, and formwork operations makes systematic OSH risk analysis necessary. In this setting, risk assessment must be close to the work activity, rather than remaining as a general list in project documentation.

Risk management provides a process for identifying uncertainty, analysing its consequences, evaluating priorities, and selecting controls. ISO 31000:2018 and SNI ISO 31000:2018 emphasise that risk information should support decision making and should be reviewed throughout the activity life cycle [6], [7].

In Indonesia, PP No. 50 of 2012 and Permen PUPR No. 10 of 2021 place OSH and construction safety within a planned management system that includes hazard control, supervision, and evaluation [2], [3].

HIRARC is commonly used as an initial tool because it connects a hazard to the likelihood of occurrence and the severity of its consequence. In contrast, FMEA adds an explicit detection parameter. Therefore, a risk that is difficult to identify or control before an incident can receive a higher priority even when its initial likelihood-severity position is not the highest. Combining the two methods makes the prioritisation process more transparent for project teams [8], [9], [13]–[16].

This study aims to: (1) identify OSH risk variables in high-rise structural work; (2) assess their initial level using HIRARC; (3) prioritise them using FMEA; (4) compare the ranking produced by both methods; and (5) formulate risk responses that are feasible for the project context. The analysis focuses only on risks that directly affect workers in structural activities; cost, quality, time, and non-safety risks are outside the scope.

II. LITERATURE REVIEW

2.1 HIGH-RISE BUILDING SAFETY AND HEALTH

High-rise projects are characterized by vertical movement, repetitive structural cycles, changing access routes, and work interfaces between different crews. Manzoor et al. [4] identify work at height, scaffolds, material handling, safety training, supervision, and personal protective equipment as important factors for accident prevention in high-rise work. Lei et al. [5] further synthesise the evidence that safety risk identification and mitigation must consider the technical work system and management practices together.

In structural work, the severity of an incident is often shaped by the location of the worker, the mass of the material, the elevation, and the time available to detect an unsafe condition. A short lapse in coordination may be enough for a worker to enter a lifting zone, work on an incomplete scaffold, or stand below unstable temporary works. Hence, practical risk control needs to combine engineering measures, administrative controls, supervision, and PPE instead of relying on a single protective layer.

2.2 HIRARC

HIRARC consists of three connected steps: hazard identification, risk assessment, and risk control. A hazard may be a source, condition, activity, or practice with the potential to cause injury or ill health. In the HIRARC assessment, likelihood represents the chance that a hazardous event will occur and severity represents the consequence if it occurs. The resulting Risk Rating is calculated as $RR = L \times S$ [8].

The likelihood and severity scales used in the thesis range from 1 to 5. A rating of 1 describes a rare event or insignificant consequence, while a rating of 5 indicates an almost-certain event or catastrophic consequence. For this study, RR values from 10 to 16 were categorized as high and values from 17 to 25 as extreme. This approach allowed the project team to identify risks that required stronger attention before work proceeded.

2.3 FMEA

FMEA identifies how a process or work activity can fail, the effects of that failure, and the relative priority for response. It uses severity (S), occurrence (O), and detection (D). Severity represents consequence, occurrence represents the probability or frequency of the failure mode, and detection represents the ability of controls or supervision to identify the risk before it results in an accident. The RPN is calculated as $RPN = S \times O \times D$ [6].

Detection is particularly relevant for construction work. A risk can be known in general but remain difficult to recognize at the exact moment when conditions deteriorate, such as when a formwork support moves under fresh-concrete load or when loose materials are placed at an edge. FMEA therefore does not replace HIRARC; it supplies a further lens for deciding which risks deserve closer monitoring and earlier intervention [7], [9], [10].

2.4 RISK RESPONSE

The response framework in this manuscript adopts four familiar options: avoid, accept, transfer, and mitigate. Avoidance means stopping or not starting work when critical safe conditions are absent. Acceptance is limited to controlled residual risk and should never be used as a rationale to tolerate a fatal exposure. Transfer means assigning specialized work to competent parties; it does not transfer the project's ultimate safety responsibility. Mitigation is the principal response in structural work and should follow the hierarchy of controls, beginning with elimination or engineering measures before administrative controls and personal protective equipment [1], [4], [5]

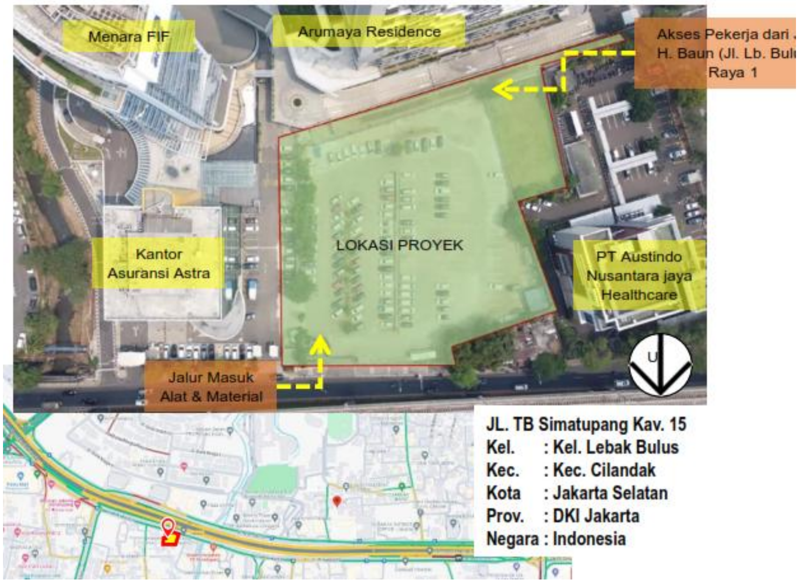

Figure 1. Location of The Arumaya Office Project
Source: project documentation, 2025.

III. RESEARCH METHODOLOGY

3.1 Research Design, Scope, and Data Sources

This research employed a descriptive quantitative case-study design. The study focused on occupational safety risks in structural work at The Arumaya Office Project, South Jakarta. The case-study approach was selected because the assessment was intended to examine risk conditions within an actual project environment, where workers, temporary structures, materials, work methods, and site conditions interact continuously.

The unit of analysis was the unsafe condition identified in each structural-work activity and its potential effect on workers. Therefore, the assessment did not use accident-frequency records as the primary unit of analysis. Instead, it evaluated potential occupational safety risks that may directly affect workers during activities such as pile-frame erection, formwork installation, scaffolding erection, material handling, concrete casting, and concrete-mixing operations.

The assessment scope was limited to occupational safety risks associated with structural work. Risks related to project cost, schedule performance, procurement, material quality, productivity, and other non-safety outcomes were not analysed in detail. This limitation was applied to maintain the focus of the study on worker exposure and unsafe conditions that require routine verification at the work front.

Primary data were obtained through risk-variable validation, a pilot survey, and questionnaires completed by 20 respondents. The respondents represented personnel who were involved in, supervised, or understood structural work at the project, including project management personnel, Health, Safety, and Environment (HSE) personnel, engineers, supervisors, field coordinators, and workers.

Secondary data consisted of project safety documents, project information, occupational safety standards, regulatory documents, and relevant literature. These sources were used to identify potential hazards, construct the questionnaire variables, and formulate appropriate risk-control recommendations.

3.2 Research Procedure and Data Collection

The research procedure was designed to ensure that the questionnaire variables were not developed solely from assumptions. The first stage involved identifying potential occupational safety hazards from project safety documents, observations of structural-work activities, construction safety standards, and relevant literature.

The second stage involved screening the identified hazards based on their relevance to structural work at The Arumaya Office Project. The preliminary variables were then validated by three project informants who understood the project conditions, structural-work activities, and occupational safety requirements. This validation process was intended to confirm that each variable represented a realistic unsafe condition that may occur during structural work.

The validation process resulted in nine occupational safety risk variables. These variables included the risk of being struck by a pile reinforcement frame during erection, being trapped by timber material, being struck by formwork timber, being struck by plywood or slab-formwork material, falling from scaffolding or height, being punctured by nails or tripping over scattered materials, being exposed to concrete spills, being thrown or struck by equipment or material, and being struck by collapsed wall formwork.

The third stage consisted of a pilot survey. The pilot survey was conducted to confirm that the wording of each questionnaire item could be understood by the intended respondents. It also ensured that the respondents could assess each variable based on their practical experience of structural-work activities.

The fourth stage involved distributing the main questionnaire to 20 respondents. The questionnaire used a five-point scale. For the HIRARC assessment, respondents evaluated the likelihood and severity of each risk. For the FMEA assessment, respondents evaluated severity, occurrence, and detection. The completed questionnaires were tabulated and processed using weighted averages to obtain representative risk scores.

The final stage involved interpreting the HIRARC and FMEA results according to the actual work context. The resulting rankings were not treated as a replacement for professional judgment. Instead, they were used to identify inspection priorities and formulate practical risk-response measures that could be verified by the project team.

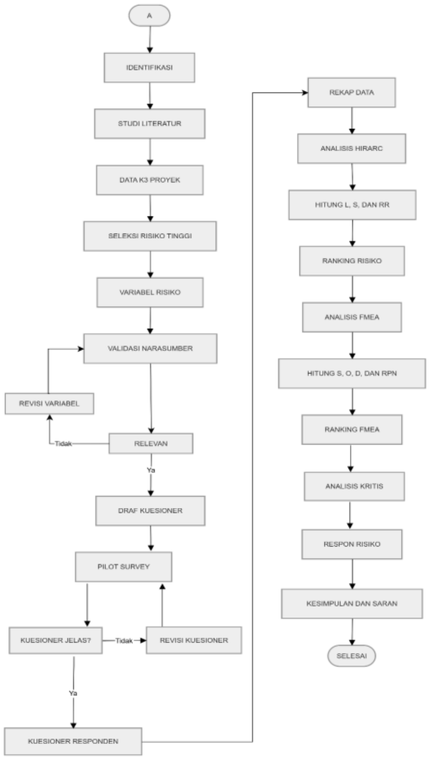

Figure 2. Research flow for the HIRARC-FMEA assessment Assessment

3.3 HIRARC and FMEA Risk Assessment

The questionnaire responses were processed using weighted averages. This calculation was used to obtain a combined score from the assessments given by all respondents for each risk parameter.

$$X = \frac{\Sigma(fi \times xi)}{N}$$

Where:
X = weighted average score
fi =number of respondents selecting scale i
xi =weight of scale i
N=total number of respondents

The weighted-average calculation was applied to all HIRARC and FMEA parameters. The resulting values represented the combined judgment of respondents who were familiar with structural-work activities and safety conditions at the project.

HIRARC was used to obtain the initial risk level for each identified hazard. The method assessed two parameters: likelihood and severity. Likelihood describes the possibility that a hazardous event may occur during the work activity. Severity describes the potential seriousness of the consequence if the hazardous event occurs.

The HIRARC risk rating was calculated using Equation.

$$RR = L \times S$$

Where:

RR=Risk Rating
L=Likelihood
S=Severity

The Risk Rating value was used to classify each risk into low, medium, high, or extreme categories. A higher Risk Rating indicates that the risk requires greater attention and more immediate control measures.

FMEA was then applied to the same risk variables to obtain a more detailed risk-priority ranking. In addition to severity and occurrence, FMEA included the detection parameter. Detection represents the ability of the existing inspection, supervision, or control system to identify the unsafe condition before it develops into an incident.

The FMEA Risk Priority Number was calculated using Equation

$$RPN = S \times O \times D$$

Where:

RPN=Risk Priority Number
S=Severity
O=Occurrence
D=Detection

A higher RPN value indicates that the risk requires a higher level of control priority. The use of FMEA complemented the HIRARC assessment because a risk may have a high consequence and occurrence level while also being difficult to detect before an incident occurs.

For example, the risk of falling from scaffolding or height was calculated using the HIRARC parameters of likelihood and severity. The risk obtained a likelihood score of 4.45 and a severity score of 4.85.

$$RR_{V5} = 4.45 \times 4.85 = 21.58$$

The same risk was then assessed using FMEA. It obtained a severity score of 4.75, an occurrence score of 4.50, and a detection score of 3.35.

$$RPN_{V5} = 4.75 \times 4.50 \times 3.35 = 71.61$$

The results indicate that the risk of falling from scaffolding or height was the highest-priority occupational safety risk in the structural-work assessment.

3.4 Risk Interpretation and Response Formulation

The interpretation of results followed two linked stages. First, HIRARC provided an initial map of the possibility and potential consequence of each hazardous event. This stage helped identify which unsafe conditions had a high initial risk level based on the combination of likelihood and severity.

Second, FMEA assessed the same risks by considering severity, occurrence, and detection. The detection parameter was important because some unsafe conditions may not be easily identified before they result in an incident. Therefore, the FMEA result was used to establish a more detailed priority order for safety control.

The final risk ranking was interpreted together with the actual work context. The ranking was not used as an automatic decision-making tool. Instead, it served as a basis for identifying activities that required closer inspection, stronger supervision, and more specific control measures.

Risk responses were formulated using four general strategies: risk avoidance, risk acceptance, risk transfer, and risk mitigation. Avoidance was applied by postponing or stopping work when the work condition was unsafe. Acceptance was only considered for controlled risks with low remaining exposure. Transfer referred to the involvement of competent personnel, specialised operators, or qualified subcontractors. Mitigation was the main response strategy because most structural-work activities still had to be performed.

The mitigation measures were developed by considering the hierarchy of control. Engineering controls included guardrails, toe boards, lifelines, bracing, temporary supports, barriers, and safe access facilities. Administrative controls included work permits, standard operating procedures, toolbox meetings, daily inspections, warning signs, housekeeping arrangements, and supervision. Personal protective equipment was used as an additional protective layer, including safety helmets, safety shoes, gloves, safety goggles, and full-body harnesses.

The formulated responses were intended to be practical and verifiable. For example, the risk of falling from scaffolding was addressed through scaffolding inspection, scaffolding tags, guardrails, toe boards, lifelines, full-body harnesses, work-at-height permits, toolbox meetings, and HSE supervision. The risk of formwork collapse was addressed through formwork inspection, bracing checks, additional supports, staged concrete casting, restricted access zones, and monitoring during concrete placement.

IV. RESULTS AND DISCUSSION

4.1 Project Context and Respondent Characteristics

The Arumaya Office Project is a high-rise office and retail development located at Jalan TB Simatupang Kav. 15, Lebak Bulus, Cilandak, South Jakarta. The project includes four basement levels and approximately 23 floors consisting of podium and tower structures. Structural work involves repetitive activities, work at height, temporary works, material movement, concrete casting, and simultaneous operations within a limited work area.

These project conditions create direct exposure to hazards such as falling from height, being struck by materials, being trapped during material handling, being punctured by nails, concrete exposure, and temporary-formwork failure. Therefore, the project was considered appropriate for the application of HIRARC and FMEA.

Table 1. Project Profile

Project profile	Information
Project name	Arumaya Office Tower
Location	Jl. TB Simatupang Kav. 15, Lebak Bulus, Cilandak, South Jakarta
Function	Office and retail building
Main contractor	PT Acset Indonusa Tbk
Construction period	24 months
Building scale	4 basement levels and approximately 23 podium/tower floors
Gross floor area	Approximately 69,756 m²
Structural activities in scope	Foundation, formwork, scaffolding, lifting, casting, and supporting activities

Figure 3. The Arumaya Office Project
Source: project documentation, 2025.

The main questionnaire was completed by 20 respondents who represented project management, HSE personnel, engineering personnel, supervisors, and workers familiar with structural work. The respondent profile indicates that most respondents had substantial construction experience, which supported the reliability of their assessments.

Table 2. Respondent Profile

Respondent characteristic	Percentage
Age 20–29 years	20%
Age 30–39 years	35%
Age 40–49 years	40%
Age 50–59 years	5%
Experience 4–6 years	15%
Experience 7–10 years	25%
Experience >10 years	60%
Senior high school / vocational school	40%
Diploma / undergraduate degree	60%

The age distribution shows that most respondents were between 30 and 49 years old. In addition, 60% of respondents had more than ten years of construction experience. This profile indicates that the assessment was largely provided by personnel with practical exposure to construction activities and safety conditions.

4.2 Validation of Occupational Safety Risk Variables

The initial risk variables were identified from project safety documents, construction safety standards, relevant literature, and project work activities. The variables were then reviewed by three project informants. All nine variables were considered relevant to structural work at The Arumaya Office Project.

Table 3. Validated Occupational Safety Risk Variables

Code	Structural work activity	Validated safety risk
V1	Foundation / erection	Falling or struck-by pile reinforcement cage during erection
V2	Formwork material handling	Caught between or struck by timber material during handling/installation
V3	Slab formwork	Struck by formwork during installation
V4	Slab formwork	Struck by plywood or slab-forming plate
V5	Scaffold installation / height work	Falling from scaffold or height
V6	Concrete casting	Nail puncture or tripping over scattered material
V7	Concrete casting	Body exposed to concrete spill
V8	Concrete mixing	Thrown or struck by moving tool/material
V9	Column/wall casting	Struck by collapsed wall formwork

The validation results confirm that the selected variables represent unsafe conditions that can directly affect workers. The variables also cover the principal structural-work hazards found in high-rise construction, including work at height, temporary structures, lifting operations, material handling, and concrete casting.

4.3 HIRARC Assessment Results

The HIRARC assessment was conducted by multiplying the weighted-average likelihood score by the weighted-average severity score. The resulting Risk Rating was used to classify the level of risk and establish an initial ranking.

The risk category was determined using the following classification:

Nilai Risk Rating	Kategori Risiko
1–4	Low Risk
5–9	Medium Risk
10–16	High Risk
17–25	Extreme Risk

The highest HIRARC score was obtained by V5, namely falling from scaffolding or height. This risk had a likelihood score of 4.45 and a severity score of 4.85.

$RR_{V5} = 4.45 \times 4.85 = 21.58$

The result indicates that the risk of falling from height was classified as an extreme risk and required immediate control measures before work continued.

Table 4. HIRARC Assessment Results

Rank	Code	Risk	L	S	RR	Category
1	V5	Falling from scaffold/height	4.45	4.85	21.58	Extreme
2	V9	Collapsed formwork	4.40	4.75	20.90	Extreme
3	V6	Nail puncture/tripping	4.25	4.70	19.98	Extreme
4	V3	Struck by formwork during installation	4.05	4.60	18.63	Extreme
5	V2	Caught between/struck by material	4.15	4.45	18.47	Extreme
6	V4	Struck by plywood/plate	3.95	4.60	18.17	Extreme
7	V8	Thrown/struck by tool or material	3.75	4.70	17.63	Extreme
8	V1	Pile reinforcement cage struck-by	3.85	4.40	16.94	High
9	V7	Concrete spill exposure	3.75	4.40	16.50	High

The results show that seven of the nine identified risks were classified as extreme risks. This finding indicates that structural work at the project involved substantial worker exposure to severe consequences, particularly during work at height, formwork installation, concrete casting, and material handling.

Risk V5 ranked first because it combined the highest severity score with a high likelihood score. The consequence of a fall from scaffolding or height can include serious injury, spinal injury, permanent disability, or fatality. The likelihood score also indicates repeated worker exposure to elevated work areas during structural activities.

Risk V9 ranked second because formwork collapse may expose workers to multiple hazards simultaneously. A formwork failure can cause workers to be struck, trapped, or buried by temporary structural components and wet concrete. The risk becomes more significant when bracing is inadequate, the formwork is not inspected, or concrete placement is performed too rapidly.Risk V6 ranked third. Although puncture wounds and trips may appear less severe than falls from height or formwork collapse, this risk is repeatedly present in daily structural work. Nails, timber offcuts, and scattered materials may obstruct work routes and cause workers to trip or lose balance. Therefore, housekeeping must be treated as a core safety control rather than a secondary task.

4.4 FMEA Assessment Results

The FMEA assessment was applied to the same nine risk variables. The method used severity, occurrence, and detection parameters to calculate the Risk Priority Number. The detection score was important because it represented the ability of existing inspection and control systems to identify unsafe conditions before they developed into incidents.

The RPN for each risk was calculated as follows:

$$RPN = S \times O \times D$$

For example, V5 obtained a severity score of 4.75, an occurrence score of 4.50, and a detection score of 3.35.

$$RPN_{V5} = 4.75 \times 4.50 \times 3.35 = 71.61$$

The result confirmed that the risk of falling from scaffolding or height remained the highest-priority risk after the detection parameter was included.

Table 5. FMEA Assessment Results

Rank	Code	Risk	S	O	D	RPN
1	V5	Falling from scaffold/height	4.75	4.50	3.35	71.61
2	V9	Collapsed formwork	4.55	4.30	3.55	69.46
3	V6	Nail puncture/tripping	4.35	4.15	3.35	60.48
4	V4	Struck by plywood/plate	4.20	4.05	3.50	59.54
5	V3	Struck by formwork during installation	4.35	4.10	3.30	58.86
6	V2	Caught between/struck by material	4.20	4.00	3.30	55.44
7	V1	Pile reinforcement cage struck-by	4.20	3.95	3.30	54.75

Rank	Code	Risk	S	O	D	RPN
8	V7	Concrete spill exposure	3.90	4.05	3.40	53.70
9	V8	Thrown/struck by tool or material	4.00	3.90	3.35	52.26

The FMEA results demonstrate that V5, V9, and V6 were consistently the three highest-priority risks. These risks required immediate attention because they combined high potential consequences, repeated exposure, and a detection score that indicated the need for closer inspection and more consistent supervision.

V4 rose from sixth place in HIRARC to fourth place in FMEA. This change occurred because the detection score of V4 was 3.50, which was higher than several other variables. The result indicates that unstable plywood or slab-formwork materials may not always be easily identified before they fall or shift. Therefore, material storage and handling conditions require routine inspection.

4.5 Comparison of HIRARC and FMEA Rankings

HIRARC and FMEA produced the same first three priorities. However, several risks changed position after the detection parameter was introduced. The comparison is presented in Table 6.

Table 6. Comparison of HIRARC and FMEA Rankings

Code	HIRARC rank	FMEA rank	Change	Interpretation
V5	1	1	0	Same highest priority; severe and repeatedly exposed height work.
V9	2	2	0	Same priority; potential catastrophic temporary-works failure.
V6	3	3	0	Same priority; frequent, close-to-worker exposure and weak housekeeping.
V4	6	4	+2	Detection concern raises priority of unstable plywood/plate material.
V3	4	5	-1	Still high; installation method and coordination require control.
V2	5	6	-1	Manual movement and worker positioning remain important.
V8	7	9	-2	Lower relative priority after occurrence and detection are considered.
V1	8	7	+1	Lifting/erection remains high-consequence and needs strict zoning.
V7	9	8	+1	Wet-concrete exposure requires PPE and work-position control.

The comparison shows that HIRARC and FMEA are complementary. HIRARC provides an initial risk map based on likelihood and severity. FMEA provides a more detailed priority ranking because it includes detection.

The unchanged ranking of V5, V9, and V6 indicates that these risks were consistently critical regardless of the assessment method. This consistency strengthens the need for focused control measures on working at height, formwork stability, and housekeeping.

The movement of V4 from rank six to rank four illustrates the practical value of the detection parameter. A material stack may look stable during a brief inspection, but plywood or slab-formwork components can shift due to poor stacking, vibration, manual handling, or congested work areas. As a result, this condition should be controlled through stable storage arrangements, stack-height limits, exclusion zones, and routine material inspections.

4.6 Risk Response Formulation

Risk responses were formulated according to the FMEA ranking because FMEA provided the more detailed priority order. The responses included avoidance, acceptance, transfer, and mitigation. However, mitigation was the main response because structural activities could not be eliminated completely from the project.

Risks with potentially fatal consequences, such as falling from height, formwork collapse, and pile-frame erection, were not considered acceptable without adequate controls. Work should be postponed when the required controls were unavailable or ineffective.

Table 7. Proposed Risk Response Matrix

Rank	Risk	Avoidance and Transfer Strategy	Main Mitigation and Corrective Action
1	V5 – Falling from scaffolding or height	Stop work when scaffolding, access, guardrails, or fall-protection systems are incomplete. Assign scaffolding work to competent personnel.	Conduct daily scaffolding inspection; use scaffolding tags; install guardrails, toe boards, and lifelines; require full-body harnesses; apply work-at-height permits; conduct toolbox meetings and HSE supervision.
2	V9 – Collapsed formwork	Delay concrete casting when formwork and bracing have not been declared safe. Use competent formwork personnel.	Inspect formwork before casting; check bracing and supports; use a checklist; apply staged concrete placement; restrict access below and around formwork; monitor formwork during casting.
3	V6 – Nails and scattered materials	Do not allow work on routes containing exposed nails, timber waste, or unsafe obstructions. Assign housekeeping responsibility to each work group.	Implement scheduled housekeeping; remove nails and timber waste; provide designated waste-storage areas; maintain safe walking routes; install warning signs; require safety shoes.
4	V4 – Plywood or slab-formwork material	Avoid stacking or moving materials when the area is unstable or workers are located below the material path. Use competent handling personnel.	Limit stack height; provide stable storage supports; use lifting aids; establish exclusion zones; keep the lower area sterile; require helmets and gloves.
5	V3 – Formwork installation	Postpone installation when methods, workers, or lifting aids are not ready. Assign installation to competent formwork workers.	Use safe installation methods; provide lifting aids; ensure worker communication; limit access to installation areas; require helmets, gloves, and safety shoes.
6	V2 – Material trapping	Avoid manual handling of heavy or oversized material when lifting aids are available. Use competent workers or operators.	Improve material-handling methods; maintain safe hand and body positions; provide clear movement routes; use lifting aids; apply hand-signal communication; require gloves and safety shoes.
7	V1 – Pile-frame erection	Suspend erection work when lifting equipment, slings, rigging, or exclusion zones are not ready. Use competent operators and riggers.	Prepare a lifting plan; inspect lifting equipment and slings; appoint rigger and signalman; use tag lines; establish exclusion zones; maintain radio or hand-signal communication.
8	V7 – Concrete spill exposure	Prevent workers from standing in direct concrete-flow or splash areas. Assign concrete equipment operation to trained personnel.	Control worker position and concrete flow; use gloves, safety shoes, closed work clothing, and goggles; provide clean water for emergency washing; conduct pouring-work supervision.
9	V8 – Equipment or material impact	Do not operate concrete mixers or similar equipment when guards are missing or the work area is congested. Use competent operators.	Inspect equipment before use; maintain safe clearance from moving parts; install barriers; ensure equipment guards function properly; require PPE; provide supervision during operation.

The proposed responses show that mitigation is the dominant strategy because structural activities must remain operational. Engineering controls, such as guardrails, lifelines, bracing, temporary supports, lifting aids, and barriers, should be prioritised because they reduce worker exposure directly.

Administrative controls remain necessary to support technical controls. These include standard operating procedures, toolbox meetings, work permits, inspection checklists, warning signs, housekeeping schedules, and supervision. Personal protective equipment should be treated as the final layer of protection rather than the only control measure.

4.7 Discussion and Practical Implications

The results indicate that the main occupational safety concern in high-rise structural work was not limited to a single work activity. The priority risks were connected to recurring structural-work conditions: work at height, temporary formwork stability, walking-route conditions, material storage, lifting operations, and concrete casting.

The most critical risk was falling from scaffolding or height. This result is consistent with the nature of high-rise structural work, where workers frequently move between elevated work platforms, scaffolding, formwork, and slab edges. The risk should be controlled before workers enter the work area. Inspections of scaffolding condition, access ladders, guardrails, toe boards, lifelines, and full-body harnesses should be performed as one integrated process.

The second-priority risk was formwork collapse. Formwork should not be treated as a minor preparation element because it functions as a temporary structure that supports concrete loads during casting. Inadequate bracing, weak supports, excessive casting rate, or poor inspection can increase the probability of failure. Therefore, formwork inspection should be integrated with the concrete-casting permit and checklist process.

The third-priority risk involved nails and scattered materials. Although the potential consequence is generally lower than a fall from height or formwork collapse, the risk is repeatedly present in daily work. The result confirms that housekeeping should be managed as a safety-control activity. Clear walking routes, removal of waste materials, and immediate treatment of exposed nails are practical actions that can reduce repeated worker exposure.

The combined use of HIRARC and FMEA was beneficial because it produced two levels of interpretation. HIRARC identified the initial risk level, while FMEA refined the order of control priorities by considering detection. The results should therefore be used by the project team as a basis for daily inspection priorities, toolbox-meeting topics, work-permit verification, and safety-control monitoring.

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